WAVELENGTH ROUTING AND SWITCHING MECHANISM FOR A PHOTONIC TRANSPORT NETWORK

Field of the invention

The invention is directed to a telecommunication network, and in particular to a wavelength routing and switching mechanism for a photonic network.

Background of the invention

The most relevant trends in the optical networking area are the increase in the network capacity and the increase in transmission reach. In response to the exponential growth of Internet use throughout the world, carriers are installing DWDM (dense wavelength division multiplexing) networks, and attempting to scale-up the existing networks by addition of equipment to support new services. It is estimated that expansion of long haul optical communication networks will be in the order of 70-150%, fueled by ever-growing data, and lately video, traffic. Currently, this expansion continues mostly based on improvements to the current transport technologies.

Carriers are also installing ultra-long reach networks, where regeneration of the signal is effected at 3,000km or more. The ultra long reach was enabled, among other factors, by the advances in transmitter and receiver design, evolution of optical amplification, employment of distributed Raman amplification combined with various dispersion compensation techniques, new encoding and modulation techniques, digital wrapper technology, etc.

However, the current D/WDM networks use point-to-point (pt-pt) connectivity, which means that all channels are OEO (optical-to-electrical-to-optical) converted at each node, which results in very complex and expensive node configurations. On the other hand, a service needs to be established between two end nodes so that in the majority of cases, OEO conversion at the intermediate nodes adds unjustifiable costs and complexity to the network.

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In addition, a point-to-point connectivity impacts negatively on the service activation time, or "time to bandwidth" (TTB). Currently, the waiting time for a new optical service in pt-pt networks is over 120 days. TTB includes two components, the network engineering time and the service activation time.

Network engineering includes generating a physical link and node design that will deliver on the specified network performance so that the provisioning application can establish optimal network operation. The output of the engineering stage feeds into the order process with detailed equipment lists and specifications along with configurations so that the installers know exactly where everything needs to be placed. A pt-pt architecture requires very complex network engineering and planning, resulting in large system turn-up time (in the order of months), involving extensive simulation, engineering and testing. In addition, the pt-pt network requires duplication of equipment for protection/ restoration in case of a fault, and, as indicated above equipment for unnecessary OEO conversion.

There is a need to provide a more efficient use of the equipment in the current D/WDM network.

There is a need to break the wavelength engineering bottleneck currently constraining the engineering-to-provisioning ratio, and for wavelengths to became available as a network resource deployable across the network.

If the equipment required to provision a new service is in place, TTB comprises only the service activation time, which includes, besides the time for back office activity and the time for connecting the equipment, the time needed for activating the service. Adding new services in a pt-pt architecture becomes more complex as the number of channels in the network grows, and therefore costly. Furthermore, as the network evolves from linear or ring configurations to mesh connectivity, automation of services becomes a difficult task.

There is a need to provide a network with the ability to automatically route and switch channels from a source node to a destination node with efficient use of OEO conversion.

Summary of the invention

It is an object of this invention to provide a method for automatically routing and switching a connection between any two switching nodes of a photonic network. In order to create this, a novel network architecture is

5   necessary, that simplifies network engineering and planning and allows automation of services. In this new architecture, the wavelengths become provisioned units, and the network provides a new service layer for the wavelength-level services.

10   Accordingly, the invention provides a method for automatically routing and switching a connection in a WDM network, comprising: receiving a request for connecting a source node and a destination node; engineering a plurality of viable regenerator paths between the source and destination nodes, based on constraints in the request and on current network

15   configuration and loading; and selecting a best path from the plurality of regenerator paths to serve the connection.

According to another aspect of the invention, automatically routing and switching a connection in a WDM network includes: engineering a plurality of viable regenerator paths between a source and a destination node, based on

20   user constraints, current network configuration and on regenerator placement rules; assigning a set of wavelengths to each the viable regenerator path based on wavelength rules and on current network loading; and selecting a best path from the plurality of regenerator paths to serve the connection.

The invention is also directed to a routing manager for a photonic WDM

25   network comprising: a routing module RM for constructing 'n' different valid link paths between a source and a destination nodes; a regenerator placement module RPM for engineering 'm' groups of viable regenerator paths for each the link path, each the each the group having 'k' regenerators; a wavelength assignment module WAM for assigning a set of wavelengths to

30   each the viable regenerator path; and a control unit for receiving a request for establishing a connection between the source node and the destination node and managing operation of the RM, the RPM and the WAM for selecting a best path available for the connection.

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According to still another aspect of the invention, a connection is automatically switched and routed over a reconfigurable photonic network by maintaining updated information on status and operation parameters of a bank of wavelength-converter/regenerator devices connected in stand-by at a plurality of switching nodes of the photonic network; investigating availability of the devices to locate a device based on the updated information; and switching the device into a communication path according to a current performance parameter of the communication path.

A method of engineering a plurality of regenerator paths between a source node and a destination node of a photonic switched network is also presented. This is accomplished by constructing a plurality of viable regenerator paths, based on current network topology data, operational parameters of all regenerators available in the WDM network, network loading data and user constraints; and selecting a best path from the plurality of regenerator paths to serve the connection.

Advantageously, the wavelength routing and switching mechanism (WRSM) according to the invention offers flexibility of provisioning in that it allows automatic wavelength route selection and path setup across the network infrastructure. The route selection is based on optical constraints, in that it works with real time photonic path and link budgets. WRSM reacts according to these budgets, balancing the network and utilizing regenerative elements where/when necessary.

A photonic network equipped with the WRSM of the invention allows important cost savings, as a network provider is not required any more to buy extra capacity for future services at the time of network deployment. This is because physical wavelength interfaces are now engineered elements, which do not need to be re-engineered during the provisioning process; the wavelengths can be deployed independent of their provisioning information. The network can be scaled-up only when needed, and the actual provisioning of the wavelength interface can be performed remotely, without human intervention at the physical interface by a simple dial.

Brief description of the drawings

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The foregoing and other objects, features and advantages of the invention will be apparent from the following more particular description of the preferred embodiments, as illustrated in the appended drawings, where:

Figure 1 shows the general architecture for a photonic network to which the present invention is applicable;

Figure 2 shows the main modules involved in the routing and switching services within the network of Figure 1, and their interaction;

Figures 3A and **3B** show the operation of the routing module, where Figure 3A shows an example of a path search tree, and Figure 3B is a flow chart illustrating the operation of the routing module;

Figures 4A and **4B** show the operation of the regenerator placement module, where Figure 4A shows an example of regenerator availability, and Figure 4B is a flow chart illustrating the operation of the regenerator placement module;

Figure 5A shows a regenerator placement search tree;

Figure 5B shows an example of how the regenerator paths are sorted;

Figure 6A shows an example of selecting a regenerator path;

Figure 6B shows how a regenerator path is selected in the example of Figure 6A according to cost and Q value;

Figure 6C shows a Q - probability of success graph used for expediting path ordering;

Figure 7 is a flow chart showing in more detail the step of path ordering of Figure 3B;

Figures 8A, 8B and **8C** show the operation of the wavelength assignment module; where Figure 8A illustrates the flow chart of the operation in the wavelength assignment module; Figures 8B and 8B show wavelength segmentation; and

Figure 9 illustrates upgrading wavelengths selection.

Description of the preferred embodiments

Figure 1 shows an example of a photonic network **1**, to which the present invention applies. The DWDM layer of network **1** is mesh-connected with flexibility points instead of traditional pt-pt nodes.

Such a network is illustrated in Figure 1. The architecture and operation of this network is described in co-pending applications "Architecture for a photonic transport network" (Roorda et al), SN not yet available, docket #1001, filed on ..., which is incorporated herein by reference.

To summarize, network **1** comprises bidirectional fiber links **10** connecting a plurality of nodes, which are nodes **A, B, C, D, E, F, Z** in the example of Figure 1. The nodes could be switching nodes **A, B, E, F, Z**, OADM (optical add/drop multiplexing) nodes **C, D**, and bidirectional optical amplifiers **8** which condition the optical signals. Local traffic **16** originating and terminating on a service platform **7** (e.g. a router, an ATM switch, an EXC, etc.) accesses the network **1** at a switching node or an OADM node (also called flexibility sites).

The optical network **1** may be partitioned into the following building blocks, which function together or, in some applications, independently:

a) Electro-optics **5**, provided for example at a switching node and an OADM node. The electro-optics system **5** performs on/off ramp of client signals onto/from the optical network and interfaces into the access multiplexing and switching systems of the network. System **5** may include for each express fiber a pool of transponders (TR), and a pool of wavelength converters/regenerators (regens). Transponders **13, 13'** are interfaces between the network and the service platform **7**. Regenerators **12** provide OEO-based wavelength conversion and/or regeneration in the network core. Also, the transmitters for both the transponders and regenerators are tunable, allowing for flexibility in selecting an A-Z path and the wavelength for that path.

b) Wavelength switches **2** are provided at switching nodes, and optical add/drop multiplexers **3** are provided at OADM nodes. Switches **2** and optical add/drop multiplexers **3** provide optical passthru, (bypassing OEO conversions), and optical add/drop of the local traffic from/to the electro-optics **5**.

c) Access multiplexing/demultiplexing and switching subsystem **4** is provided at switching nodes, and at some OADM nodes, such as node **C**. The access subsystem routes the add and drop channels between the electro-optics sub-system **5** and the respective switch **2** or OADM **3**. It

distributes individual wavelengths from the line system to the transponders/regenerators, and aggregates individual wavelengths from the transponders/ regenerators onto the line system.

d) Optical line subsystem post/pre amplification and line amplifier subsystem **8** is provided on the links between the nodes. It comprises post, pre and line amplifiers and the associated dispersion and power management equipment necessary for ultra-long haul propagation along the line.

Network **1** is scalable; if new fibers are added between the flexibility sites, the respective optical amplifiers and the associated dispersion and power management equipment can be readily connected at an OA site by adding a respective amplifier shelf, etc. As well, nodes may be scaled-up by adding modules to the respective switch, OADM, access system as/when needed.

A signaling and control system SCS **9** is provided between all nodes and the optical line subsystem. SCS **9** allows topology discovery and fault monitoring, and photonic layer network management. As new resources are added to the network, system **9** updates the network topology database **12** with the new resources, their location and connectivity, operating parameters, etc. It is to be noted that while the database **12** is shown as a unique block, instances of this database are available at each node. Based on this topology information, a network and element management system **11** monitors and controls operation of the network nodes and their connectivity, and provides node and network inventory data and various metrics. This information is stored for both current and future use in a network topology database NTD **15**. It is to be noted that this database is not necessarily provided on a unique hardware support as shown, and it can be distributed between the nodes.

The network is also provided with a system for monitoring network resources utilization (NRU) shown generically at **16**. System **16** uses the resource data from the network topology database **15** and monitors the utilization of these resource using pre-set thresholds. Whenever a threshold is violated, an alarm is provided on terminal **14** at a network operations center NOC **17**, so that the network resources can be re-deployed for

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optimal utilization, if possible. If after the optimization attempt, some resources are still under-provisioned, the operator may place a purchase order in advance from the time when the respective resources are indeed needed.

5   Figure 1 also shows two connections **A-Z** and **C-D**. The **A-Z** connection originates at switching node **A**, passes through switching nodes **B** and **D** in optical format, and is dropped at node **Z** to service platform **7**. Connection **C-D** originates at flexibility site **C**, passes through node **E** in optical format, is OEO converted at node **Z** for wavelength

10   conversion/regeneration and is dropped at node **D**. As shown for connection **C-D**, network **1** has the ability to determine if a channel needs regeneration, looks for a regenerator **12** available at one (in this example) or more flexibility sites on the route of that channel, and allocates the regenerator to the respective path to process the signal accordingly.

15   Figure 2 illustrates a logical overview of the modules of the network and element management system **11**, which are involved in wavelength routing and switching. This figure also shows the interaction between the modules.

The term "A-Z path" refers to a connection between a source node,

20   generically referred to as node **A**, and a destination node, generically referred as node **Z**.

A call management block **31** provides a routing management platform **30** with a connection request. The request can also be referred to as a "dial", "redial" or "call", and refer in this context to a request for a new connection

25   between source node **A** and sink node, **Z**. A request defines certain conditions, and generally has some constraints, set according to the class of services applicable to the respective user.

Routing management platform **30** comprises a routing module RM **33**, a regenerator placement module RPM **35** and a wavelength assignment

30   module WAM **36**. A routing management controller **32** receives the call from block **31**, operates modules RM 33, RPM 35 and WAM 36 to generate a list of possible best paths. The regenerator placement module **35** orders the path according to their chances of success and maintains this list until a path is successfully setup. It presents the paths from the list, one by one, to the call

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management **31**, which in turn attempts to set-up a path. If the first path on the list fails, the call management **31** requests the next path from the RMC **32** the next path, and so on, until a path is successful.

A Q calculator **39 is** available for use by the modules of the routing management **30**, as it will be seen as the description proceeds. The Q calculator is a module provided by an optical engineering platform **38**, for estimating a Q quality factor based upon knowledge of the topology and characteristics of the network. It encapsulates the physics of the propagation of signals through equipment and tries to estimate the amount of distortion to a signal due to physical effects, such as cross-talk between wavelengths, to produce an estimate of the quality of the signal referred to as the Q factor.

Routing module **33** is responsible for finding 'n' number of paths, also called link paths, between source node **A**, and destination node **Z**. The term 'link path' is intended to indicate that each such A-Z connection is comprised of a different succession of links between end node **A** and **Z**. While 'N' link paths may be available for an A-Z connection, only 'n' link paths are selected in the first instance by the routing module **33**. The number 'n' can be selected by the user, based for example on the overall system cost versus the setup time. The examples shown assumes that n=4. RM **33** operates according to a set of constraints, which are received with a service request from a call management block **31,** as it will be seen later under the title" Routing Module".

Regenerator placement module **35** is responsible for determining 'm' sets of regenerator paths for each link path. A set comprises all regenerator paths with the same number 'k' of regenerators, each having the respective 'k' regenerators placed at a different combination of 'k' nodes. For example, a 1st set may have no regenerators, a 2nd set may have one regenerator, etc. The maximum number of regenerators in a set is given by the number of intermediate nodes. While 'M' sets may be available for a link path, RPM **35** only selects 'm' sets in the first instance. The number 'm' is again chosen by the user, based upon the loss calculated along the path, or using a more sophisticated Q estimation, based upon the required setup time. The examples shown below assumes m=4. This module operates based on regenerator placement constraints or rules **37** to select the best regenerator

path for the respective service request, as it will be seen later under the title" Regenerator Placement Module".

The wavelength assignment module **36** is responsible with finding a single end-to-end wavelength, or a set of wavelengths for each selected

5   regenerator path based again on wavelength constraints or rules **37**. This module also provides a wavelength upgrade path for the 0-regenerator and 1-regenerator paths, and upgrades the weakest link (flexibility point-to- flexibility point) for the regenerator paths with k>2, as it will be seen later under the title" Wavelength Assignment Module".

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Routing Module **33**

The routing module **33** of Figure 2 operates as described next in connection with Figures 2, 3A and 3B. Figure 3A shows an example of a path search tree, and Figure 3B is a flow chart illustrating the operation of the

15   routing module.

As shown in Figure 3B, a request is received from the call management **31** for an A-Z path, step **40**. Routing module **33** declares node **A** as the root node, step **41**. For the general case, we denote the root node with R(i) and the links originating in a node are denoted with L(j). It is to be

20   noted that call management **31** works always with the routing module **33** of the root node R(i).

Next, RM **33** builds a search tree **ST** as in the example of Figure 3A, using topology data imported from the database **15**, as shown at **15'**, and applying any constraints that were specified with the path request, steps **42,**

25   **43**. Module **33** also associates a link weighting function to each link L(j), as shown in step **44**. The weights are denoted with LW(j), and may be defined as shown in EQ1 by way of example.

LW(j) = (link length * link cost) + (estimated link equipment cost) + (α *

30   link loading cost) + (cost for type of fiber)

(EQ1)

where:

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α is a binary threshold based on the load of the link. α is set to '0' or '1' and the correct setting at which α becomes '1' is to be determined by simulating various network topologies with various loading thresholds. For example, if the link-loading threshold has been set to 80%, then whilst the link is less than 80% loaded this parameter is 0. Once the link load increases above 80%, α becomes 1. 'Link weighting cost' is defined as the total cost of using the link. Link cost is the amortized cost given per unit of link length (e.g. km).

'Link length' is the physical length of the link. The purpose of this parameter is to bias paths towards shorter routes.

'Estimated equipment cost of link' takes into account only equipment along the link, i.e. the line subsystem (optical amplifiers, DCMs, etc.).

'Link loading cost' is defined as the average percentage load on a link. For example, if there are 5 fibers between two flexibility points, the average loading cost is the average cost across these 5 fibers. The purpose of this parameter is to move traffic away from the most heavily used routes as the network fills up. Other criteria may be envisaged to estimate link loading cost.

'Amortized cost for type of fiber' is associated with the type of fiber along the link e.g. LEAF™, True-Wave™ classic, etc.

Shown in dotted lines on Figure 3B is a variant of path processing, whereby if the LW(j) is higher than a threshold, step **45**, the respective link is abandoned, step **47**. In this variant, the weighting factor for the next link is calculated, in steps **43, 44, 45**, until the weights for all links at the respective tree level and originating from the root R(j) are determined, branch NO of decision block **45** and branch YES of decision block **46**. The threshold can be for example a maximum cost for a certain class of service associated with the call (i.e. privileges for the user who placed the request). The threshold can also be a minimum value.

Variants where all links are processes are also possible, in which case block **45** is not necessary.

If all links from a root node were processed, module **33** determines if node Z was reached, step **48**, and if not, it moves to the next node at the

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same level of the tree, or at the next level, step **50**. Operations **42- 48** are repeated for these levels of the tree **ST**, and for all nodes at the level.

Once node Z is reached, meaning that an A to Z link path was found, as shown by branch YES of decision block 48, a path weight PW(i) is calculated for the respective link path, and the path is stored, step **49**. PW(i) may again be a cost function for the final path, which could be defined for example as:

$$PW(i) = (\text{ingress node cost}) + (\text{egress node cost}) + (\text{estimated regen costs for path}) + \Sigma\,(\text{link weight costs}), \qquad \textbf{(EQ2)}$$

where,

'Ingress Node Cost' is the amortized cost associated with node A, i.e. the cost of the transponder.

'Egress Node Cost' is the amortized cost associated with node Z, i.e. the cost of the transponder.

'Estimated regen costs for the path' is estimated for example by considering that a regenerator must be inserted in the path every 3000km. This cost is also amortized. It is to be understood that this distance is given here as a practical example for explaining the operation of the RM **33**; the reach of a regenerator depends on the particular regenerator used. Furthermore, it is possible to extend the estimated regenerator cost to other regenerator types; for example, a hybrid RZ/NRZ type may be used. Nonetheless, the type and reach of the regenerators are irrelevant to the invention, it is important to correctly estimate the cost taking into account the available devices. It is also possible to use a Q estimation for the path in order to determine the number of regenerators needed and their cost.

'Link weight costs' are the weights LW(j) assigned to each link along the path. These are summed and added to the path cost.

The next path is determined in same way, until 'n' link paths are constructed and stored, as shown by branch NO of decision blocks **51, 52**.

In the event that 'n' link paths cannot be found due to physical constraints or because the weight function for a particular request is exceeded

on all remaining branches of the search tree, branch NO of decision blocks **51,** and branch YES of decision block **52,** the less than 'n' link paths that have been found are given to the regenerator placement module **36.** This is shown by branch NO of decision block **54.** In the case that no path at all could be found after the entire search tree has been examined, the network and element manager **11** provides the operator at NOC **17** with appropriate alarms, branch YES of decision block **54.**

Once all 'n' (or less) link paths are built, and the associated path weights PW are calculated, the link paths are passed to the regenerator placement module 35 and wavelength assignment module 36, step 53.

It is possible to apply another mechanism to obtain one path only. For example, a shortest path first algorithm may be used, in which case the path weight may be calculated using EQ3:

$FW(i)$ = (ingress node cost) + (egress node cost) + (estimated regen costs for path) + Σ [(link length * link cost) + (estimated link equipment cost) + (α * link loading cost) + (cost for type of fiber)]
EQ3

Again, it is to be noted that the above equations are provided by way of example, any other ways of determining an estimated cost for the path(s) may be equally employed.

If RPM **35** and the WAM **36** cannot find a feasible route, branch NO of decision block **55,** module **33** continues to build the search tree, by returning to step **52,** to find another link path. If the regenerator placement and wavelength assignment have been successful, the paths found after step **55** are ordered in step **56,** as it will be seen in connection with Figure 7. The ordered paths are returned to routing management control **32,** step **57,** which presents them in sequential order to the call management **31,** step **58.** Now, the network and element management system **11** can initiate physical implementation (lighting the A-Z path). System **11** tries to set-up the paths starting with the best path on the list, and if path set-up is successful, branch YES of decision block **59,** RM **33** destroys the stored paths, step **20.** On the

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other hand, if the path cannot be set-up, the next best path is tried, steps **91** and **50**. If no path from the best paths list can be set-up, branch YES of decision block **50**, the operator at NOC **17** or the setup software in the case of a UNI request is informed of this failure.

5   The routing management platform **30** also takes into consideration the type of protection associated with an A-Z request. A 0:2 path request is handled as two 0:1 requests. This means that for a 0:2 path request, the routing management platform will first find a principal A-Z path, and then provide this principal path back to the routing module **33** as a constraint, so

10   that the module finds a secondary path. Persons skilled in the art will be aware of other approaches to find 0:2 path directly instead of using two 0:1 path requests with constraints. One approach is to find a cycle within the topology graph which includes the source and destination nodes. By splitting the cycle into two paths starting at the source node and ending at the

15   destination node the 0:2 path can be obtained. Another approach would be to use a Ford-Fulkerson augmented path algorithm to find a 2 unit flow from source node to destination node and then use a tree search technique to find two paths between the source node and the destination node. This approach has the advantage that it can be extended to find 0:k paths where the Ford-

20   Fulkerson augmented path algorithm is used to find a k unit flow from source node to destination node followed by a tree search technique to find k paths.

The routing module **33** supports two different scenarios with respect to selection of the end transponders, depending if the transponders are pre-provisioned or not.

25   In the case where the transponders are pre-provisioned, the route selection is constrained at the source node **A** and sink node **Z**. That is, the first link between node **A** and the first intermediate node along the path is fixed; flexibility of routing comes only after the first intermediate node. Also, since the end transponder at node Z is pre-provisioned, routing must ensure

30   that the path enters site Z on the side where the sink transponder is connected.

In the case where the transponders are post-provisioned (floating case) routing is not constrained at either the beginning or end of the path, and the module makes the decision as to which transponder to use.

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Regenerator Placement Module

Figures 4A and 4B show the operation of the regenerator placement module **35**. Figure 4A gives an example of the type and number of

5 regenerators available at flexibility sites **A, B, C, D,** and **Z** along a link-path A-Z, and Figure 4B illustrates the flow chart with the operation of the regenerator placement module **35** for the example of Figure 4A.

In this example, there are two types of regenerators available, a RZ-type (return-to-zero encoding of data) regenerator and a NRZ-type (non-

10 return-to-zero) regenerator. Each type has a different reach, and for the purpose of illustration, let's consider that the reach of the NRZ regenerators is approximately 1500km and the reach of RZ regenerators is approximately 3000km. Also, let's assume that a NRZ regenerator costs half of the price of a RZ regenerator; both regenerator reach and cost are taken into

15 consideration by module **35**.

As seen in Figure 4B, a link path selected by routing module **33** is input first to module **35**, as seen in steps **53** on Figure 3B. The regenerator availability data is provided by DTS **15**, step **60**, and module **35** attempts to find viable regenerator paths, steps **61, 62**.

20 The regenerator placement module **35** attempts to place the regenerators in the most optimal position along the link path by building a 'regenerator availability tree' or 'regenerator tree' **25** as shown in Figure 5A. As the name suggests, the tree provides a list of valid regenerator vs. reach combinations. The regenerator tree has 'branches' for all possible

25 combinations of number (k) and position of regenerators for the respective a link path. In other words, the module analyzes all variants with a regenerator at the first level of the tree, in this example node **B** (branch **71**), node **C** (branch **72**), node **D** (branch **21**), or no regenerators at all (branch **22**). Next, module **35** tries all variants with a regenerator at the second level of the tree,

30 which are: from node **B**, a regenerator at node **C** (branch **74**), or at node **D** (branch **75**), or a branch going directly to end node **Z** (branch **73**). Similarly, regenerator paths are formed with a first regenerator at node **C**, and the second level providing for a regenerator at node **D** (branch **26**) or going directly to node **Z** (branch **27**). The third level is constructed in the same

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manner, and it includes branches **76, 79, 78**, and **28**, while level four includes only branch **77**.

At the same time, the module abandons the branches that are not viable, based on the regenerator presence, type and reach of the end transponders and regenerators at the intermediate nodes. A variant is 'viable' and declared a 'regenerator path' for a given link path, if the optical signal originating at node **A** can reach node **Z** with or without regenerators switched in the link path.

In the example of Figure 5A, valid variants for the first level are the regenerator paths including branch **71** to node B and branch **72** to node **C**, which nodes are at a 2000km and respectively 3000km distance from node **A**. The signal from node **A** cannot reach node **D** or **Z** without regeneration, since distances A-D and A-Z are greater than the reach of an RZ transponder. Therefore branches such as **21** are invalid, and they are not pursued further.

In addition, as the distance A-B is 2000km, the transponder at node A needs to be of RZ type, which has a reach of 3000km, rather than of NRZ type, which cannot reach node **B**. Therefore branches like **23** are also abandoned. The abandoned branches are crossed with an X in Figure 5A. It is noted that the type and reach data specified above are by way of example to show how the viable regenerator paths are selected.

As discussed above, the type of transmitter at the beginning of the path determines the type of regenerator(s) that can be used along the entire path. For example, since the transponder at **A** needs to be of type RZ to reach node **B**, any regenerators used along this regenerator path must be of the RZ type. Nonetheless, module **35** is free to choose the equipment type after the tree was built if both a NRZ and RZ regenerator paths were found (not in the example of Figure 4A).

By applying reach and type constraints to the example of Figure 4A and abandoning the paths that are not viable, (marked by 'X's' on Figure 5A), five viable regenerator paths may be constructed for the example of Figure 4A, and they are shown in Figure 5B. Of course, the viable regenerator paths may be determined using a variety of alternative techniques, including a wave propagation simulation, or a Q estimation; the intent is to determine if 'branches' can transport the signal from the source to destination.

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Returning to Figure 4B, module **35** groups the regenerator paths into 'm' sets, where preferably m=4, step **63**. However, in the example analyzed here, there are only three sets available (m=3), shown in Figure 5B, namely a 1st set with the 1st path having one regenerator (k=1), a 2nd set with the 2nd, 3rd

5 and 4th paths having each two regenerators (k=2), and a 3rd set with the 5th path having three regenerators (k=3). In this case, as in other circumstances where the module cannot return the 'm' sets, the module processes further as many regenerator paths as it can build. Reasons for not finding 'm' regenerator paths could be for example too few intermediate nodes on the

10 respective link path (e.g. k is maximum 3 in the example of Figure 3A), a path for k=0 is not viable (i.e. the length of the path is greater than the reach of the transponder at node A), etc.

There could also be cases where no sets with k=0 or 1 are possible. In such cases, module **35** starts building a first set with 2 regenerators, a second

15 set with 3 regenerators, a third set with 4 regenerators and a fourth set with 5 regenerators. Alternatively, the cases for k=0,1 may not be considered altogether, to reduce the time for path selection.

Returning now to Figure 5B, module **35** operates on three sets, as four sets are not available in this example. Since the 2nd set comprises three

20 regenerator paths, a determination of the best regenerator path needs to be made based on the path performance. However, path performance cannot be estimated until after the wavelength assignment module assigns wavelength for all paths, as shown in step **64**, Figure 4B. It is to be noted that step **64** is further detailed in Figure 6B.

25 In a 0-regenerator case (not shown in Figure 5B as it is not applicable to the above example) a continuous wavelength must be assigned to the entire regenerator path, since there is no opportunity for wavelength conversion between nodes **A** and **Z**. The term 'continuous wavelength' is used for a segment of a path, which uses the same carrier wavelength along

30 one or more links; the wavelength changes at a regenerator site provided with a wavelength converter.

On the other hand, for the regenerator paths of the 1st, 2nd and 3rd sets, it is less desirable to use a continuous wavelength from A-Z, in order to reduce wavelength fragmentation; the continuous wavelength paths are

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required primarily for 0-regenerator cases. Therefore, module **36** assigns to regenerator paths wavelengths that are already fragmented, since the opportunity to change the wavelengths along such a path is always available at the regenerator sites.

5   Let's assume that module **36** located a plurality of fragmented wavelengths for each regenerator path; the reference numerals above the connections between the nodes of Figure 5B, which identify the tree branches in Figure 5A, correspond to a certain distinct wavelength.

The prioritization may be performed based on the minimum Q value of

10   the path, steps **65, 66**. In this case, Q value is first estimated at each regenerator site and at the end transponder, using Q calculator **39** provided by the optical link engineering module (OLE) **38** (see Figure 2). An example of Q values is shown on Figure 5B for all regenerator nodes and the end node Z.

15   The Q_{est_min} of the respective paths is determined as being the lowest Q value calculated along the path, since a path is only as strong as it's weakest link. The Q_{est_min} value for the paths in the example of Figure 5B are 4.0 for the 2nd path, 4.0 for the 3rd path and 4.5 for the 4th path. The path with the highest Q_{est_min} value in the 2nd set is the 4th path (Q=4.5) in this case.

20   The paths in each set (here in the 2nd set) are next ordered by the path cost, step **67**. As indicated above, the price of an RZ regenerator is assumed to be considerably greater than the price of an NRZ regenerator. However, all paths in the above example use RZ regenerators, so that the paths in the 2nd set have the same cost, let's say $200,000.

25   Alternatively, the paths may be ordered first by the cost and then by Q_{est_min}.

The number of regenerators available at each site is next considered, step **68**; these numbers are shown in Figure 4A. Again, since only RZ regenerators are being considered in this example, the number of NRZ

30   regens available has no bearing. To reiterate, the 2nd path requires an RZ regenerator at node **B** and one at node **C**, the 3rd path requires an RZ regenerator at node **B** and one at node **D**, and the 4th path requires an RZ regenerator at node **C** and one at node **D**. Since there are fewer RZ

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regenerators available at node **D** (7) than at node **B** (8) in this example, the 2nd path is better than the 4th path. Since there are fewer regenerators available at site **D** than at site **C**, the 2nd path is better than the 3rd path. The 2nd path is therefore the best choice for the 2nd set, and the 4th path is the second choice from regenerator availability point of view.

A weighting function is employed at step **69**, which sorts the regenerator paths taking into account the estimated Q values, the path cost, and the regenerator availability. Below is an example of such a cost function:

(Ordered Path Weighting) = (α * Q balance) + (β * Regen cost) + (δ * Regen availability),

(EQ4)

Where:

α = Weighted % for Q balance importance in biasing selection

β = Weighted % for Regen cost importance in biasing selection

δ = Weighted % for Regen availability in biasing selection

For example, α = 50%, β = 50% and δ = 0%. Also, the percentage splits for both the Q balance ordering and the regenerator cost ordering could be:

1st place = 50% of the weight

2nd place = 30% of the weight

3rd place = 10% of the weight

4th place = 8% of the weight

5th place = 2% of the weight

6th place and worse = 0% of the weight.

Evaluating the results from the Q balance ordering and the regenerator cost ordering, and putting these results into EQ4, the best regenerator path of the 2nd set is the 4th path. If a regenerator path in the set has the same path weight as another, then an arbitrary decision is made as too which regenerator path to use for that set.

Namely, a Q balance of 50% total path weight contribution, gives a weight of 25% to 4th path (50% of the 50%) since it came 1st, and gives a weight of 7.5% to 2nd and 3rd paths.

The weight of the regenerator cost is the same for all paths, namely 8.333% (50% total path weight contribution).

As for this example $\gamma=0$, regenerator availability is not considered, for simplicity. Therefore the total weights are, from EQ4:

5   2nd path = 7.5 + 8.333 = 15.833

3rd path = 7.5 + 8.333 = 15.833

4th path = 25 + 8.333 = 33.33

EQ4 results in selection of the 4th path as the best path in the 2nd set.

10   Ideally, the output of step **69** in the flowchart of Figure 4B, are 'n' link paths, each with 'm' sets of regenerator paths, which are returned to the route management control **32**. If path selection, regenerator placement and wavelength assignment have been successful, the paths must be ordered as shown in step **57** of Figure 3B.

15   Ordering of the best paths can be for example based on the path cost and Q performance, as shown in Figures 6A, 6B, 6C and 7. Figure 6A shows an example of the final path vs. regenerator matrix, which in this case has 32 cells. Figure 6B shows how a regenerator path is selected in the example of Figure 6A according to cost and Q value and Figure 6C shows a Q -

20   probability of success graph used for expediting path ordering.

The matrix of Figure 6A is ordered in terms of lowest cost, step **101**. The entry point to this matrix is always the lowest cost path (as determined by applying the cost function EQ3), which is placed in the top left hand corner **80** of the matrix. The number of all possible link and regenerator path

25   combinations is n x m, which is 16 for the preferred 'n' and 'm' values (n=m=4). The term 'wavelength upgrade' refers in this specification to re-assigning another wavelength to a regenerator segment, selected to perform better than the current wavelength. Specifically, some wavelengths can reach further than others; the performance of a wavelength also depends on the

30   spacing between the channels on the respective regenerator segment.

In this example 0 and 1 regenerator paths are present; for the 0-regenerator paths there is only one possible upgrade path and for the 1-regenerator path there are three possible upgrade combinations possible.

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This means that in the 0 and 1 regenerator case there are additional 4 path sets for each of the 4 paths; giving a final matrix of size 32. In the case where the first regenerator path set had 2 or more regenerators, a wavelength upgrade will only be provided for the weakest segment (flexibility point-

5   flexibility point) along the path; hence, in this case the final matrix will have less than 32 cells. It should be noted that in the 2 or more regenerator case all wavelengths along the path could be upgraded and in this case the final matrix would have more than 32 cells.

The ideal method for finding the best available solution for the A-Z path

10   is to attempt to set-up all paths in steps **59** of Figure 3B, starting with the lowest cost path and working towards the highest cost path which also has a higher Q value and hence a greater chance of success. The duration of these operations impact on the total time for setting-up the new service. If we assume that the path set-up time is 8 seconds and the path tear-down time is

15   4 seconds (12 seconds for a try), trying all paths could take a waiting time of 32x12-4 = 380 seconds (6.333 minutes) for the worst case scenario when only the last path was found to work. It is to be noted that 4 seconds are deducted from the waiting time since there is no teardown time for the last path. As mentioned previously in the case where the first regenerator path

20   set is a set with two or more regenerators, there will be less than 32 cells, because all segments along the path will probably not have wavelength upgrades.

In the ideal case where there is time to try every path, path ordering starts by trying the 0 regenerator path shown at the top left hand corner of

25   Figure 6A, and works through the matrix one row at a time from left to right until a path is successfully setup.

However, in the case that the customer is not willing to wait until all paths are tried, an alternative strategy may be employed, as illustrated in Figure 6A, by the arrows, Figure 6B, Figure 6C and shown by the steps of

30   Figure 7.

Figure 6B gives an example of costs and Q values of the 0 regenerator Path 1, Path 2 and Path 3 where $Cost_{P1} = Cost_{P2}$ and $Cost_{P2} < Cost_{P3}$, while $Q_{P2} < Q_{P1} < Q_{P3}$. It is to be noted that the example of Figure 6A and 6B use

the terms path 1, path 2, path 3 and path 4 for the link-paths; no confusion should be made with the 1st to 5th paths of Figure 5B.

Let's assume that path 1 does not work, in that the Q_{est_min} value is 4.0 and a higher Q is requested. RM **33** checks next path 2. Path 2 has a lower

5   Q_{est_min} than path 1, hence a lower chance of success. Moving next to path 3, this has a Q value higher of that of path 1 and path 2, hence, path 3 is selected, even though the cost of this path is higher than that of path 2. The logic behind this is that since path 1 failed with a Q of 4.0 the chance of path 2 working is even lower since it has a Q of 3.8 and since the amount of time to

10   find a workable solution is limited the path selections made must be moving towards a higher Q value and hence a greater probability of success. Path 3, 0 regenerators is thus the next path selected from the matrix of final paths.

Figure 6C extends this concept by introducing Q thresholds, which are defined to guide the selection process and reduce the waiting time necessary

15   to find a workable path. For example, if the threshold is set between 4.0 and 7.0, then only paths with Q values above 4.0 will be tried, and the assumption made is that paths with a Q greater than 7.0 have a 99.99999% probability of success. As before, the Q_{est_min} value for a path is the lowest Q value calculated along the path.

20   Making now the assumption that the maximum waiting time for a particular class of service is 104 seconds, for the worst-case scenario where the very last path tried is the one that works, 104 seconds would allow the system to try a total of S= 9 paths (12x9-4) out of the 32 possible. This determination is shown in step **102** of Figure 7. In step **103**, 'R' paths with the

25   higher chances of success are selected out of all potential n x m paths (hereinafter called the 'best paths'). In the example of Figure 6A, 'R' is 4, and the four cells with higher probability of success are highlighted. The probability for success is given for example by:

30    $$P(success) = (R \text{ paths with } Q_{est\_min} > Q_{maintenance} + Q_{margin}) \quad \textbf{EQ5}$$

Q_{margin} is a pre-determined, hard coded margin for success.

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Next, in step **104**, the remaining time is calculated, namely the difference between the waiting time and the effective time used by trying the 'R' best paths. In the example, the effective time is $t = 4x12-4 = 44$ seconds. Subtracting this from the waiting time gives an additional time of (T-t)=104-

5   44=60s. As testing a path takes 12s, and there are 60s left, this means that 5 additional paths (S-R) can be tested in the waiting time.

The selection criteria is taken one step further by attempting to space path selections evenly between the lower and upper Q thresholds and the number of paths which can be tried in the allowed time, as illustrated in Figure

10   6C. A probability of success versus Q value graph **18** may be employed to try and select paths on an evenly spaced basis from 4.0 to 7.0. In this example it is assumed that a path with a Q value above 7.0 will always work, and hence the highest probability paths selected are with Q values ≥7.0. Also, for S-R = 5, we could try to select paths that have Q values at 0.5 intervals between 4.0

15   and 7.0. Figure 6C shows the selection for this example. Let's say that the paths selected are, in the order of cost and Q value: path 3, 0 regenerators; path 4, one regenerator; path 2, one regenerator, wavelength upgrade; path 1, one regenerator, wavelength upgrade; path 3, one regenerator, wavelength upgrade; and path 1, one regenerator, wavelength upgrade. The selection

20   continues, and the next paths to be selected will most probably be the paths highlighted in Figure 6A.

Routing management **30** maintains the list of paths, as generically illustrated by database **37** on Figure 2. The final ordered path selections are returned sequentially by routing management control **32** to call management

25   **31** in the determined order in which the path setup should be tried.

Wavelength assignment module 36

Figures 8A, 8B and 8C show the operation of the wavelength assignment module. Figure 8A illustrates the flow chart with the operation of

30   the wavelength assignment module **36**, and Figures 8B and 8C show a wavelength segmentation example.

The wavelength assignment module **36** in conjunction with the regenerator placement module **35** are used by the regenerator placement module as shown in Figure 3B, step **55**, and more precisely by the

regenerator placement module **35**, as shown in step **64**, Figure 4B. The wavelength assignment module attempts to find a single wavelength *or a set of wavelengths that would enable a connection along each of the regenerator paths.*

5   Wavelength Assignment module **36** provides the following functionality:

- Computes a route for working (and protection if required) traffic using the available resources.
- Computes the lowest cost route based on capacity utilization (optimal regenerator placement), OEO utilization, photonic constraints and

10   administrative constraints, such as specific sites where regenerators must/ must not be used

- Considers a Wavelength Fill Sequence.
- Resolves wavelength blocking.
- Considers fiber types/ matching of fiber.

15   - A bandwidth reservation mechanism for both shared and dedicated restoration bandwidth considers predicted photonic performance at the time of restoration, in order to ensure a high probability of connection success during a restoration event.

Module **36** processes all regenerator paths m for each of the n link

20   paths, and attempts to assign wavelengths to the path. In the case of the path sets with 0 regenerators, the selected wavelength must be continuous from A-Z. In a regenerator path with 'k' regenerators, up to *k+1* wavelengths may be used. In the first instance of wavelength assignment on paths with 'k' regenerators, where k>0, access to wavelengths that are continuous from A-Z

25   is initially restricted. The reason for this is that when a regenerator exists in the path, better use of network resources may be obtained by using shorter reach wavelengths. Wavelength assignment starts by receiving the regenerator form module **35**, step **90**.

Figures 8B and 8C show an example of wavelength segmentation, for

30   better illustrate how module **36** functions. In the example shown in Figure 8B, is λ2 already used between nodes **A** and **B** and λ3 is used between nodes **B** and **Z** (the used wavelengths are shown in dotted lines doubled by a solid line). While using a continuous wavelength λ1 as shown for case 1 on Figure

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8C without wavelength conversion at intermediate sites **B, C, D** is one
solution, this option is initially restricted, as discussed above. Thus, a better
solution in the case of a 1-regenerator path, is to place the regenerator at
node **B**, as shown in Figure 8C, case 2, and to use λ3 on link A-B and λ2 on

5   links B-C, C-D and D-Z, which is available on these links. Case 2 is
preferable to case 1.

Preferably, wavelength assignment module **36** is provided with tables,
step **92**, giving a list with preferred channels versus loading and route lengths.
Such tables may be provided for various types of fiber, and stored and loaded

10   at system startup.

Preferred Channels vs. loading and regenerator-regenerator distance

Load %	Route Length		
	< 1000 km	1000-2000 km	>2000 km
25 (200Ghz)	G1 1,5,9,13,81,85,89,93	G2 17,21,25,29,65,69,73,77	G3 33,37,41,45,49,53,57,61
50 (100Ghz)	G4 1,5,9,13,81,85,89,93, 3,7,9,15,83,87,91,95	G5 17,21,25,29,65,69,73,77, 19,23,27,31,67,71,75,79	G6 33,37,41,45,49,53,57,61, 35,39,43,47,51,55,59,63
>50 (50GHz)	G7 any 1-16 or 81-96	G8 any 17-32, 65-80	G9 Any 33-64

15   In step **93**, module **36** finds a λ set for the first regenerator path of the
first link path, based on the fiber loading, and using the above table. The most
desirable group of wavelengths are always considered first. If no wavelength
can be found within this group, a group of wavelengths with greater reach
than currently required is tried, but starting at the lower end of the group. If no

20   wavelength group with greater reach exists, then a wavelength group with
less reach can be used, but starting at the top end of this group. For
example, the assignment can start with G3, if no wavelength can be found
within this group, G6 is considered, then G9 and then G2.

Let's consider again the example of Figure 4A, also assuming a less

25   than 25% loading on the fiber.

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The length of the entire path (from node A to node Z) is 5500km. In the case of a regenerator path with k=0 (no regenerators), the signal has to reach 5500km. Using the table, the wavelengths with the greatest chance of driving this distance are those of group 3 (G3) which have approximately 200GHz

5   spacing. If one of these wavelengths is not available continuously for the entire path, then wavelengths from G6 in the 50% loading section are considered (with approximately 100GHz spacing). If a continuous wavelength still does not exist, any wavelength from G9 in the >50% loading section is considered with approximately 50GHz spacing). If a continuous wavelength

10   can still not be found, and since a group with a higher reach does not exist, group G2 will be used, staring with the top end of this group, which is wavelength 93. This process continues until a wavelength is found or every wavelength has been considered.

Alternatively, non-table implementations may also be used. It is

15   possible to use Q estimates for a given wavelength for a specific path. A variety of strategies may be devised for wavelength upgrades; the intent is to find a better wavelength than the one currently used. Preferably, such strategy needs to be driven by network cost and path setup time.

RPM **35** builds the 1thpath (see Figure 5B) as a one-regenerator path,

20   with the regenerator placed at flexibility point C. Again, the >2000km wavelengths of G3 with a less than 25% loading are considered and if a wavelength can not be found, G2 will be used, staring with the top end of this group. If no wavelength can be found on the segment from node A to node C, the 1st path is flagged as incomplete. If a wavelength on the segment A - C is

25   found, a search for a wavelength for segment C to Z begins.

RPM selected the 4th path as the best path for the 2 regenerators set. From Figure 5B, it can be seen that the 4th path requires a regenerator at flexibility points **C** and **D**. Segment A-C has 3000km, so the search for a wavelength begins again in G3. As in the previous case, if no wavelength is

30   found then group G2 is considered. If no wavelength can be found for segments **A-C**, **C-D** and **D-Z**, the 4th path is flagged as incomplete. If a wavelength for segment A-C is found, then a search for a wavelength for segment **C-D** begins in group G2, and if this is successful, a search begins for a wavelength for segment **D-Z** in group G1 (**D** to **Z** is 500 km), until a

wavelength set is found for the entire path, when the set is stored against the path data, step **97**. If a wavelength set is not found for the respective regenerator path, branch NO of decision block **110**, steps **95, 96** are performed and module 36 attempts to find a wavelength set for the next regenerator path.

As also seen in Figure 5B the only path with 3 regenerators is the 5th path. As in the previous cases, the search starts with the first segment **A-B** and in the most desirable group, which is G2, with the second segment **B-C** in G1, for the third segment **C-D** in G2 and for the last link in G1. Same rule as above apply. If no wavelength can be found for segments **A-B, B-C, C-D** or **D-Z**, then the 5th regenerator path is flagged as incomplete, step **95**.

For the 0 and 1 regenerator path sets (k=0,1), wavelength upgrades may be provided for each segment of the path, as shown in step **99**. Figure 9 illustrates the concept of wavelength upgrades. As shown in the above table, $\lambda 32$ and $\lambda 43$ are correct suggested wavelengths for the given distances and link loading. I.e. $\lambda 32$ is suitable for section **A-C** which has 1500km, and $\lambda 42$ is suitable for section **C-Z** which has 1850km. However, on setup, either or both fail. The solution is to upgrade the wavelengths rather than adding a regenerator, since a wavelength upgrade has a much lower cost.

Let's assume that wavelengths $\lambda 42$ and $\lambda 44$ are available for upgrade, step **99**. Chances are that the path can be set-up if $\lambda 32$ is upgraded to $\lambda 42$, which falls the >2000km section of the table, as shown in step **110**. However, no benefit can be obtained if $\lambda 43$ is upgraded since this already falls within the >2000km section of the table. Hence, in the example shown in Figure 9, there is only one choice for a wavelength upgrade path, which is to upgrade the section **A-C**. There are three combinations for a one regenerator path for the segment, 8 upgrades combinations for 2 regenerator paths, 16 for 3 regenerator paths, etc. A selection is preferably made based on cost, step **111**.

If however no upgrade set can be find, module **36** flags the regenerator path accordingly and begins assigning wavelengths to the next regenerator paths, step **110** and the module 36 attempts to find a wavelength set for the next regenerator path. For k>2, a wavelength upgrade is only provided for the

weakest segment along the path, where the weakest segment is defined as the segment with the lowest Q value.

Once module **36** has determined that all regenerator paths were allocated appropriate λ-sets, step **112**, the completed regenerator paths are returned to the regenerator placement module, step **66** in Figure 4B, for path selection. If not, module 36 continues assigning λ-sets to the remaining regenerator paths.

Numerous other embodiments of the invention may be envisaged without departing from the scope of the invention, as defined by the claims.

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